Properties of superconducting Mo, Mo_2N and trilayer $Mo_2N/Mo/Mo_2N$ thin films

E. M. Barrentine[a], T. R. Stevenson[a], A. D. Brown[a], A. E. Lowitz[b], O. Noroozian[a], K. U-Yen[a], N. Eshan[a], W. T. Hsieh[a], S. H. Moseley[a], E. J. Wollack[a]

[a]NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA

[b]University of Wisconsin-Madison, Madison, WI 3715 USA

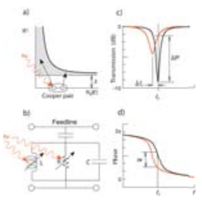
3EPo2H-02: 59

Abstract

We present measurements of the properties of thin film superconducting Mo, Mo_2N and $Mo_2N/Mo/Mo_2N$ trilayers of interest for microwave kinetic inductance detector (MKID) applications. Using microwave resonator devices, we investigate the transition temperature, energy gaps, kinetic inductance, and internal quality factors of these materials. We present an Usadel-based interpretation of the trilayer transition temperature as a function of trilayer thicknesses, and a 2-gap interpretation to understand the change in kinetic inductance and internal Q as a function of temperature.

Superconducting Microwave Resonators & MKIDs

- A MKID is a superconducting resonator which experiences a shift in resonance frequency, f_0, and resonance quality factor, Q, when excited by photon(s).
- This is due to an increase in the kinetic inductance, L_k, and loss in the resonator.
- We are interested in understanding the details of these materials' kinetic inductance as a function of temperature, which is related to the resonator's optical response, and probes the energy gap Δ of the superconducting material and the kinetic inductance fraction α of the resonator.

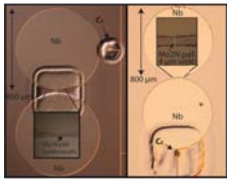


$$1-\left(\frac{f_0(T)}{f_0(0)}\right)^2=\frac{\alpha\cdot dL_k(T)}{1-(1-\alpha)\cdot dL_k(T)}$$

$$\alpha=\frac{L_k(0)}{L_k(0)+L_{geometric}}\quad dL_k=1-\frac{L_k(0)}{L_k(T)}$$

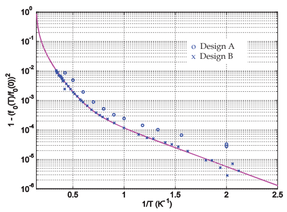
$$dL_k(T)=1-\frac{\Delta(T)}{\Delta(0)}\tanh\left(\frac{\Delta(T)}{k_BT}\right)\quad [1]$$

Mo_2N Devices & Measurements



Design A Design B

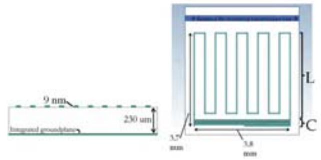
- We fabricated and measured two different lumped-element resonator designs incorporating small-volume Mo_2N films for the inductor and large area Nb capacitors.
- The Mo_2N films were deposited using DC magnetron reactive sputtering and etched in phosphoric acid-based etchant.
- Mo_2N thickness = 73 nm & T_c = 7 K.
- Measurements in He-3 fridge from 4 K to ~300 mK with one-port setup for Design A and 2-port setup for Design B.

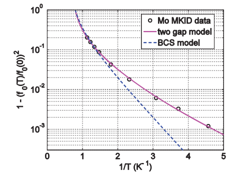


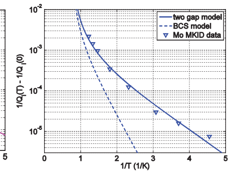
Fit parameter	2-gap Model Fit
Δ_1/Δ_{BSC}	0.87
Δ_2/Δ_{BSC}	0.24
η	0.012
α	0.12

- Unlike a 1-gap BCS model, the 2-gap model provides an excellent fit across the full temperature range for both Design A & Design B.
- Alternatively, adding a stray light background power, or a TLS response, to 1-gap models did not provide a good fit.
- The repeatability of this 2-gap modeled behavior in two Mo_2N resonator geometries, and two measurement setups, is evidence that this behavior is intrinsic to the superconducting film.

Mo Devices & Measurements



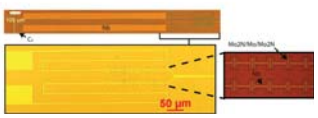


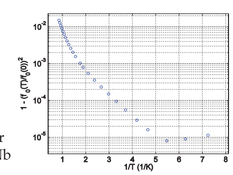


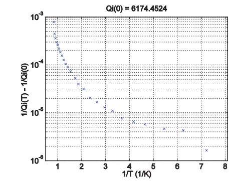
- We fabricated and measured a lumped-element resonator design with a Mo meandered inductor and interdigitated capacitor.
- The Mo film was deposited using DC magnetron reactive sputtering and wet-etched. Mo thickness = 9 nm & T_c = 1.26 K
- Measurements were done in ADR cooled to 150 mK. Fits to both f_0 and Q vs. T provide better constraints on parameters and show a significantly better fit to a 2-gap model.

Fit parameter	1-gap Model Fit	2-gap Model Fit
Δ_1/Δ_{BSC}	1.0	0.70
Δ_2/Δ_{BSC}	-	0.40
η	-	0.11
α	0.505	0.27

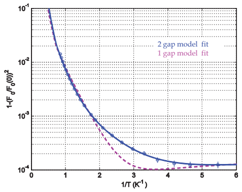
Trilayer $Mo_2N/Mo/Mo_2N$ Devices & Measurements





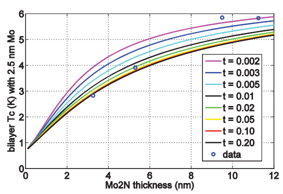


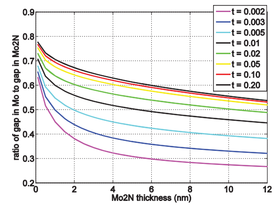
- We fabricated and measured a lumped element resonator with meandered Nb & $Mo_2N/Mo/Mo_2N$ inductor and Nb capacitors.
- The $Mo_2N/Mo/Mo_2N$ thin films were deposited using DC magnetron reactive sputtering and etched in phosphoric acid-based etchant.



Fit parameter	1-gap Model Fit	2-gap Model Fit
Δ_1/Δ_{BSC}	0.43	0.67
Δ_2/Δ_{BSC}	-	0.18
η	-	0.02
α	0.20	.50

- We derived a relation between the T_c and energy gap ratio of our multilayer films and the film thicknesses by following the Martinis-Usadel theory approach [21]. We see agreement within uncertainties of transmission factors t and Mo & Mo_2N T_cs.





- These devices ($Mo_2N/Mo/Mo_2N$ thickness ~15 nm & T_c=3.15 K.) were cooled in a dilution refrigerator to 7 mK and heated up to 1 K.
- f_0 vs T data was fit to 1-gap and 2-gap models with a TLS contribution. The 2-gap model shows a good fit across the full T range, while a 1-gap + TLS model is inconsistent with the data. Q vs T data also shows a 2-gap form.
- Additionally, optical absorption measurements show quasiparticle excitation ≥ 100 GHz, below BSC gap, and consistent with a subdominant gap from model fits.

Nitrides & a 2-gap Model of Superconductivity

- Nitride films are of interest for MKIDs due to high L_k, high electrical resistivity (which allows for easier impedance matching to transmission lines), high internal Q, and low TLS noise. Multilayer films may also allow for tuning T_c with improved uniformity.
- Nitride superconductors, such as TiN, NbTiN, and TiN/Ti/TiN films, have shown deviations in the temperature dependence of L_k from simple Mattis-Bardeen behavior [2-7]. In these cases, a 'broadening' model has been applied to explain these effects at higher temperatures T > 0.15 T_c [6,8].
- We consider an alternative 2-gap model that provides an unified explanation for such deviations at all temperatures. The model is motivated by the observations of 2-gap behavior in MgB_2 [9-15].
- In a 2-gap model the superconductor is treated as two- superconducting fluids, each characterized by an energy gap, but coupled such that there is a single measurable T_c:
$$dL_k(T)=(1-\eta)\cdot dL_{k,1}+\eta\cdot dL_{k,2}.$$
- Here η is the fraction of the superconducting kinetic inductance which is the sub-dominant gap fluid [10]. We also allow that the energy gap may deviate from the BSC gap, Δ_{BSC}, predicted by the measured T_c, by way of a temperature-independent 'gap ratio' : Δ_1/Δ_{BSC} and Δ_2/Δ_{BSC} where $\Delta_{BSC}(T)$=1.67k_BT_c [16].
- We apply this 2-gap theory in two different, but analogous, cases. In the case of our Mo and Mo_2N devices, there is the potential for 2-band superconductivity because there are multiple energy bands cross the Fermi surface in Mo [17-19] and Mo_2N[20-21], just as in MgB_2. For our $Mo_2N/Mo/Mo_2N$ trilayer devices, instead of two conduction bands, the two coupled electron systems are spatially separated in the different material layers of the trilayer, coupled by transmission across the interfaces.

Conclusions

We find evidence of 2-gap behavior in superconducting Mo, Mo_2N and trilayer $Mo_2N/Mo/Mo_2N$ thin films resonators by examining kinetic inductance vs. T data. This behavior is repeated across different resonator geometries and measurement setups. Such a 2-gap interpretation might provide a compelling alternative explanation to deviations from Mattis-Bardeen behavior in nitrides, and some elemental superconductors, across a wide temperature range.

References

1. A. L. Fetter, J. D. Walecka, Quantum Theory of Many-particle Systems, Courier Dover Publications, 2003, p. 463.
2. J. Gao et al., "A titanium-nitride near-infrared kinetic inductance photon-counting detector and its anomalous electrodynamics," *Appl. Phys. Lett.*, vol. 101, 2012, p. 142602.
3. Leduc et al. "Titanium nitride films for ultrasensitive microresonator detectors," *Appl. Phys. Lett.*, vol. 97, 2010, p. 102509.
4. M. R. Vissers et al. "Low loss superconducting titanium nitride coplanar waveguide resonators,"*Appl. Phys. Lett.*, vol. 97, 2010, p. 232509.
5. R. Barends et al., "Contribution of dielectrics to frequency and noise of NbTiN superconducting resonators," *Appl. Phys. Lett.*, vol. 92, 2008, p. 223502-1.
6. E. F. C. Driessen et al., "Strongly Disordered TiN and NbTiN s-Wave Superconductors Probed by Microwave Electrodynamics," *Phys. Rev. Lett.* vol. 109, Sept 2012, p. 107003.
7. M. R. Vissers et al., "Proximity-coupled Ti/TiN multilayers for use in kinetic inductance detectors," *Appl. Phys. Lett.*, vol. 102, 2013, p. 232603.
8. R. C. Dynes, V. Narayanamurti, and J. P. Garno, "Direct Measurement of Quasiparticle-Lifetime Broadening in a Strong-Coupled Superconductor," *Phys. Rev. Lett.* vol. 41, Nov 1978, p. 1509.
9. M. Iavarone et al., "MgB2: directional tunnelling and two-band superconductivity," *Supercond. Sci. Technol.*, vol. 16, 2003, p. 156–161.
10. M. S. Kim et al., "Reflection of two-gap nature in penetration depth measurements of MgB_2 film," *Phys. Rev. B*, vol. 66, Aug 2002, p. 064511.
11. A. A. Golubov et al., "Multiband model for penetration depth in MgB_2," *Phys. Rev. B*, vol. 66, August 2002, p. 054524.
12. S. Souma et al., "The origin of multiple superconducting gaps in MgB_2," *Nature*, vol. 423, May 2003, p. 65.
13. F. Bouquet et al., "Phenomenological two-gap model for the specific heat of MgB_2," *Europhys. Lett.*, vol. 56, 2001, p. 856–862.
14. A. Y. Liu, I. I. Mazin, and J. Kortus, "Beyond Eliashberg Superconductivity in MgB2: Anharmonicity, Two-Phonon Scattering, and Multiple Gaps," *Phys. Rev. Lett.* vol. 87, Aug 2001, p. 087005-1.
15. H. J. Choi et al., "The origin of the anomalous superconducting properties of MgB_2," *Nature*, vol. 418, Aug 2001, p. 758.
16. H. Padamsee, J. E Neighbor, and C. A. Shiffman, "Quasiparticle Phenomenology for Thermodynamics of Strong-Coupling Superconductors," *J. Low Temp. Phys.*, vol. 12, 1973, p. 387.
17. J. Haglund, G. Grimvall, T. Jarlborg, "Ab initio method for band-structure calculations on structurally disordered materials: Vibrational properties of 4d transition metals," *Phys. Rev. B*, vol. 47, April 1994, p. 9279.
18. A. R. Jani, G. S. Tripathi, N. E. Brener, and J. Callaway, "Band structure and related properties of molybdenum," *Phys. Rev. B*, vol. 40, July 1989, p. 1593.
19. R. J. Iverson– and L. Hodges, "Molybdenum: Band Structure, Fermi Surface, and Spin&rbit Interaction," *Phys. Rev. B*, vol. 8, August 1978, p. 1429.
20. D. A. Papaconstantopoulos et al., "Electronic properties of transition-metal nitrides: The group-V and group-VI nitrides VN, NbN, TaN, CrN, MoN, and WN," *Phys. Rev. B*, vol. 31, January 1985, p. 752.
21. P. Marksteiner, J. Redinger, and P. Weinberger, "Electronic Structure and Calculated X-Ray Photoemission Spectra of Substoichiometric Cubic Molybdenum Nitride," *Z. Phys. B*, vol. 62, 1986, p. 443-449.
22. J. M. Martinis, G. C. Hilton, K. D. Irwin, D. A. Wollman, "Calculation of T_c in a normal-superconductor bilayer using the microscopic-based Usadel theory," *Nucl. Instrum. Meth. A*, vol. 444, 2000, p. 23-27.